

# The Bimodal Colors of Centaurs and Small Kuiper Belt Objects

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**Abstract.** Ever since the very first photometric studies of Centaurs and Kuiper Belt Objects (KBOs) their visible color distribution has been controversial. That controversy gave rise to a prolific debate on the origin of the surface colors of these distant icy objects of the Solar System. Two different views attempt to interpret and explain the large variability of colors, hence surface composition. Are the colors mainly primordial and directly related to the formation region, or are they the result of surface evolution processes? To date, no mechanism has been found that successfully explains why Centaurs, which are escapees from the Kuiper Belt, exhibit two distinct color groups, whereas KBOs do not. In this letter, we readdress this issue using a carefully compiled set of  $B - R$  colors and  $H_R(\alpha)$  magnitudes (as proxy for size) for 253 objects, including data for 10 new small objects.

We find that the bimodal behavior seen among Centaurs is a size related phenomenon, common to both Centaurs and small KBOs, *i.e.* independent of dynamical classification. Further, we find that large KBOs also exhibit a bimodal behavior of surface colors, albeit distinct from the small objects and strongly dependent on the 'Haumea collisional family' objects. When plotted in  $B - R$ ,  $H_R(\alpha)$  space, the colors of Centaurs and KBOs display a peculiar  $\mathcal{N}$  shape.

**Key words.** Kuiper belt: general

## 1. Introduction

Discovered just 20 years ago (Jewitt & Luu 1993), the Kuiper Belt holds a vast population of icy bodies orbiting the Sun beyond Neptune. Stored at very low temperatures ( $\sim 30$ -50 K), the Kuiper Belt Objects (KBOs) are expected to be well-preserved fossil remnants of the solar system formation. Presently,  $\sim 1600$  KBOs have been identified and classified into several dynamical families (see Appendix A and Gladman et al. 2008, for a review). KBOs which dynamically evolve to become Jupiter Family Comets (JFCs) form a transient population, the Centaurs, with short-lived chaotic orbits between Jupiter and Neptune (Kowal et al. 1977; Fernandez 1980; Levison & Duncan 1997).

Between 1998 and 2003, we witnessed a debate on the surface colors of KBOs and Centaurs. One team used very accurate surface colors and detected that KBOs were separated into two distinct color groups (Tegler & Romanishin 1998, 2000, 2003). Other teams did not find evidence for such color bimodality (Barucci et al. 1999; Jewitt & Luu 2001; Hainaut & Delsanti 2002). Careful reanalysis of the data by Peixinho et al. (2003) indicated that only the Centaurs display bimodal colors, *i.e.* they are distributed in two distinct color groups, one with neutral solar-like colors, and one with very red colors. KBOs on the other hand exhibit a broad continuous color distribution, from

neutral to very red, with no statistical evidence for a color gap between the extrema (Tegler et al. 2008, for a review).

The relevance of this controversy lays on two possible interpretations: i) KBOs and Centaurs are composed of intrinsically different objects, with distinct compositions, which probably formed at different locations of the protosolar disk, ii) KBOs and Centaurs are originally similar but evolutionary processes altered them differently, hence their color diversity. Most research focused on the latter hypothesis, offering little improvement on our understanding of the color distributions. Luu & Jewitt (1996) proposed that the competition between a reddening effect of irradiation of surface ices (Thompson et al. 1987) and a bluing effect due to collisional induced resurfacing of fresh, non-irradiated, ices might generate the observed surface colors. The same authors, however, rejected this model as being the primary cause of the color diversity, due to the lack of predicted rotational color variations (Jewitt & Luu 2001). Based on the same processes, Gil-Hutton (2002) proposed a more complex treatment of the irradiation process, by implying an intricate structure of differently irradiated subsurface layers. However, the collisional resurfacing effects became very hard to model, thus making it very hard to provide testable predictions. Later, Thébault & Doressoundiram (2003) showed that the collisional energies involved in different parts of the Kuiper Belt did not corrobo-

rate the possible link between surface colors and non-disruptive collisions.

Delsanti et al. (2004) refined the first-mentioned model by considering the effects of a possible cometary activity triggered by collisions, and a size/gravity-dependent resurfacing. Cometary activity can modify the surface properties through the creation of a neutral-color dust mantle. Jewitt (2002) suggested that this process could explain why no JFCs are found with the ultra-red surfaces seen in about half of the Centaurs. It has also been proposed that the sublimation loss of surface ice from a mixture with red materials may be sufficient to make the red material undetectable in the visible wavelengths (Grundy 2009). These might explain the Centaur color bimodality, as long as all were red when migrating inwards from the Kuiper Belt. Although promising, these models did not provide an explanation for the color bimodality of Centaurs, as they fail to reproduce the bluest colors observed and their frequency.

## 2. Motivation for This Work

We find it striking that the objects with both perihelion and semi-major axis between Jupiter and Neptune’s orbits, the Centaurs — by definition —, would display a different color distribution than physically and chemically similar objects with a semi-major axis slightly beyond Neptune’s orbit, as is the case for Scattered Disk Objects (SDOs), for instance, or any other KBOs. There is no evident physical consideration that would explain the apparently sudden ‘transition’ in surface color behavior (from bimodal to unimodal) precisely at Neptune’s orbital semi-major axis  $a_N = 30.07$  AU. This difference between Centaurs and KBOs is particularly puzzling since there is neither a sharp dynamical separation between them, (the definition is somewhat arbitrary), nor a clearly identified family of KBOs in their origin. Although SDOs are frequently considered as the main source of Centaurs, Neptune Trojans, Plutinos, and Classical KBOs have been demonstrated as viable contributors (Horner & Lykawka 2010; Yu & Tremaine 1999; Volk & Malhotra 2008, respectively). Further, Centaurs possess short dynamical lifetimes of  $\sim 5 \cdot 10^5 - 3 \cdot 10^7$  yr before being injected as JFCs or ejected again to the outer Solar System (Horner et al. 2004). If some surface evolution mechanism, dependent on heliocentric distance, is responsible for the bimodal behavior of Centaurs, it must be acting extremely fast such that no intermediate colors are ever seen among them. Besides surface color bimodality, the most distinctive characteristic of Centaurs compared to ‘other’ KBOs is their small size. Known KBOs are mostly larger than Centaurs, simply because they are more distant and thus smaller objects are harder to detect.

In this work, we address the issue of the color distributions of Centaurs and KBOs. We present new data on seven intrinsically faint (thus small) KBOs and three Centaurs, combined with a new compilation of 253 published  $B-R$  colors, and available  $m_R(1, 1, \alpha)$  magnitudes, or  $H_R(\alpha)$ , *i.e.* absolute magnitude non-corrected from phase effects, and some identified spectral features. We study this large sample of colors (including objects from all dynamical families) versus absolute magnitude as a proxy for size, with the implicit assumption that surface colors are independent of dynamical classification. We present the most relevant results, found in  $B-R$  vs.  $H_R(\alpha)$  space.

## 3. Observations and Data Reduction

Observations of 7 KBOs and 1 Centaur were taken at the 8.2 m Subaru telescope, on 2008–07–02, using  $0.''206/\text{pix}$

Table 1: Filters specifications

Filter	8.2m Subaru		UH 2.2m	
	Wavelength (Å)	Width	Wavelength (Å)	Width
B	4400	1080	4480	1077
R	6600	1170	6460	1245

FOCAS camera in imaging mode with  $2 \times 2$  binning (2 CCDs of  $2048 \times 4096$  pixels, Kashikawa et al. 2002). Weather was clear with seeing  $\sim 0.7''$ . We used the University of Hawaii UH 2.2 m telescope, to observe 2 Centaurs on 2008–09–29, with the  $0.''22/\text{pixel}$  Tektronix  $2048 \times 2048$  pixels CCD camera. Weather was clear with seeing  $\sim 0.9''$ . Both telescopes are on Mauna Kea, Hawaii, USA. Images from both instruments were processed using IRAF’s CCDRED package following the standard techniques of median bias subtraction and median flat-fielding normalization.

Standard calibration was made observing Landolt standard stars (Landolt 1992) at different airmasses for each filter, obtaining the corresponding zeropoints, solving by non-linear least-square fits the transformation equations, directly in order of  $R$  and  $(B-R)$ , using IRAF’s PHOTCAL package. The characteristics of the filters used on each telescope were essentially equal (Tab. 1). Subaru’s data was calibrated using Landolt standard stars: 107-612, PG1047+003B, 110-230, Mark A2, and 113-337, taken repeatedly at different airmasses. UH2.2m’s data was calibrated, analogously, using the stars: 92-410, 92-412, 94-401, 94-394, PG2213-006A and PG2213-006B. These stars have high photometric accuracy and colors close to those of the Sun. We have used the typical extinction values for Mauna Kea,  $k_B = 0.19$ , and  $k_R = 0.09$  (Krisicunas et al. 1987, and CFHT Info Bulletin #19). All fits had residuals  $rms < 0.02$ , which were added quadratically to the photometric error on each measurement. Targets were observed twice in B and twice in R bands, to avoid object trailing in one long exposure. Each two B or R exposures were co-added centered in the object, and also co-added centered on the background stars. The former were used to measure the object, the latter to compute the growth-curve correction. The time and airmass of observation were computed to the center of the total exposure. We applied growth-curve correction techniques to measure the target’s magnitudes using IRAF’s MKAPFILE task (for details, see Peixinho et al. 2004). Observation circumstances and results are shown in Table 2.

## 4. Compilation of Data

We compiled the visible colors for 290 objects (KBOs, Centaurs, and Neptune Trojans) for which the absolute magnitude in R or V band was accessible (*e.g.* with individual magnitudes and observing date available), and surface spectra information for 48 objects, as published in the literature to date (Feb. 2012). We computed the absolute magnitude  $H_R(\alpha) \equiv m_R(1, 1, \alpha) = R - 5 \log(r \cdot \Delta)$ , where  $R$  is the R-band magnitude,  $r$  and  $\Delta$  are the helio- and geocentric distances in AU, respectively. In this compilation, 253 objects have  $B-R$  color available which is the focus of this paper (see Table A.1), and 48 have also spectral information. The description of the compilation method is presented in Appendix A. Sun-Object-Earth phase angles  $\alpha$  are, typically, less than  $1.5^\circ$  for KBOs and less than  $4^\circ$  for Centaurs. Measurements of magnitude dependences on the phase angle for

Table 2: Observational circumstances and photometric results of this work’s data

Object	Dyn. Class*	Telescope	UT Date	$r$ [AU]	$\Delta$ [AU]	$\alpha$ [°]	R	B-R	$H_R(\alpha)$
(130391) 2000 JG <sub>81</sub>	2:1	Subaru	20080702UT07:24:58	34.073	34.817	1.2	23.12±0.03	1.42±0.06	7.75±0.06
(136120) 2003 LG <sub>7</sub>	3:1	Subaru	20080702UT09:42:53	32.815	33.659	1.0	23.54±0.05	1.27±0.09	8.32±0.05
(149560) 2003 QZ <sub>91</sub>	SDO	Subaru	20080702UT13:08:33	25.849	26.509	1.7	22.48±0.03	1.30±0.05	8.30±0.03
2006 RJ <sub>103</sub>	Nep. Trojan	Subaru	20080702UT14:07:50	30.760	30.534	1.9	22.27±0.02	1.90±0.04	7.40±0.02
2006 SQ <sub>372</sub>	SDO	Subaru	20080702UT11:45:34	23.650	24.287	1.9	21.55±0.02	1.78±0.03	7.71±0.05
2007 JK <sub>43</sub>	SDO	Subaru	20080702UT08:08:13	23.113	23.766	1.9	20.73±0.02	1.40±0.03	7.03±0.02
2007 NC <sub>7</sub>	SDO	Subaru	20080702UT11:30:49	20.090	20.916	1.7	21.19±0.02	1.28±0.03	8.07±0.02
(281371) 2008 FC <sub>76</sub>	Cent	Subaru	20080702UT11:13:05	11.119	11.793	3.8	19.79 ±0.02	1.76±0.02	9.18±0.04
2007 RH <sub>283</sub>	Cent	UH2.2m	20080929UT12:43:47	17.081	17.956	1.6	20.85 ±0.03	1.20±0.05	
2007 RH <sub>283</sub>	Cent	UH2.2m	20080929UT12:57:51	17.081	17.956	1.6	20.90±0.03	1.28±0.06	
mean...								1.24±0.07	8.44± 0.04
2007 UM <sub>126</sub>	Cent	UH2.2m	20080929UT08:56:52	10.191	11.177	0.9	20.43±0.03	1.21±0.05	
2007 UM <sub>126</sub>	Cent	UH2.2m	20080929UT09:06:41	10.191	11.177	0.9	20.53±0.03	0.92±0.04	
2007 UM <sub>126</sub>	Cent	UH2.2m	20080929UT09:16:17	10.191	11.177	0.9	20.38±0.02	1.12±0.04	
mean...								1.08±0.10	10.16±0.04

**Notes.** \* Dynamical classes are: Centaur, Scattered Disk Object (SDO), Neptune Trojan (object located in 1:1 mean motion resonance with Neptune), 2:1, and 3:1, (objects located in 2:1 or 3:1 mean motion resonance with Neptune, respectively). For details on the classification see Appendix A

these objects, *i.e.* phase coefficients  $\beta$ [mag/°], are scarce but, so far, do not show evidence for extreme variability presenting an average value of  $\beta = 0.11 \pm 0.05$  (Belskaya et al. 2008). From the linear approximation  $H_R(\alpha = 0^\circ) \approx H_R(\alpha) - \alpha\beta$ , by not correcting the absolute magnitude from phase effects we are slightly overestimating it. We will deal with this issue in Sec. 5.

Recent works have shown that there is no strong correlation between object diameter  $D$  and geometric albedo  $p_V$ , nor between geometric albedo  $p_V$  and absolute magnitude  $H_R$  (Stansberry et al. 2008; Santos-Sanz et al. 2012; Vilenius et al. 2012; Mommert et al. 2012). However, from the 74 diameter and albedo measurements of Centaurs and KBOs made using Herschel and/or Spitzer telescopes, published in the aforementioned works, we verify that  $H_R$  and  $D$  correlate very strongly with a Spearman-rank correlation of  $\rho = -0.92^{+0.03}_{-0.02}$ , with a significance level  $SL \ll 0.01\%$  (error bars computed using bootstraps, for details see Doressoundiram et al. 2007). Consequently, absolute magnitude is a very good proxy for size.

## 5. An $\mathcal{N}$ -shaped Doubly Bimodal Structure

In Fig. 1 we plot  $R$ -band absolute magnitude  $H_R(\alpha)$  (proxy for object’s size) against  $B - R$  color for all ( $n = 253$ ) objects in our database. The cloud of points forms a recognizable  $\mathcal{N}$  shape with an apparent double bimodal structure in color. The smaller objects (upper part of the plot) show a bimodal  $B - R$  distribution. Although apparently dominated by Centaurs, this bimodal distribution also includes KBOs of similar  $H_R(\alpha)$ , which suggests that **the bimodal structure in  $B - R$  color is a property of the smaller objects in general, regardless of their dynamical family**. This bimodality appears to disappear for objects with  $H_R(\alpha) \lesssim 7$  where the  $B - R$  color distribution seems unimodal. Most interestingly, we note that towards the larger objects (lower part of the plot) the colors suggest the presence of another bimodal behavior, with the gap between the two groups shifted towards the blue with respect to the ‘small’ object bimodality. This new ‘large’ object bimodality is explicitly reported for the first time.

When performing hypotheses testing one should adopt a critical value of significance  $\alpha$ . The value  $\alpha$  is the maximum proba-

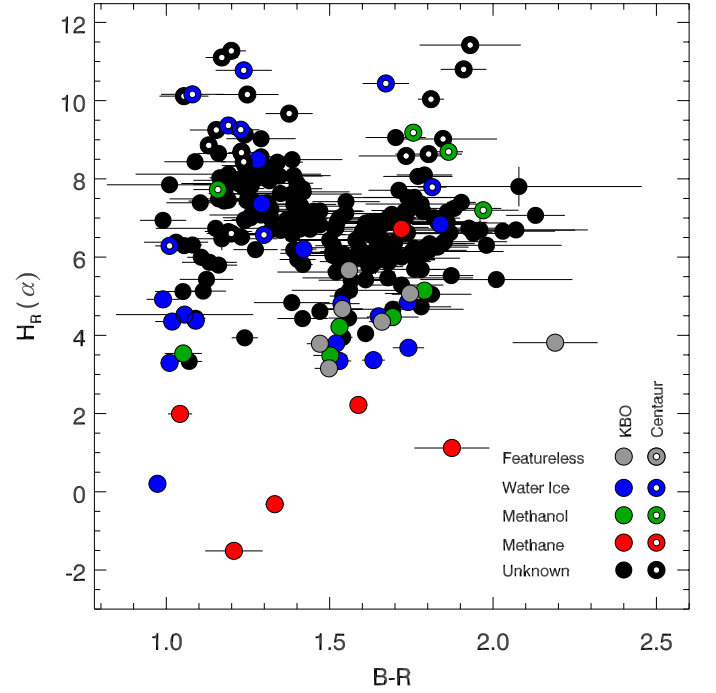


Fig. 1:  $B - R$  vs.  $H_R(\alpha)$  plot of all 253 objects. KBOs are represented by solid circles and Centaurs by white dotted solid circles. Objects with  $H_R(\alpha) \geq 6.8$  separate into two color groups with a ‘gap’ centered at  $B - R \sim 1.60$ . Objects with  $H_R(\alpha) \leq 5.0$  also show statistical evidence for separation in two colors groups but with a ‘gap’ centered at  $B - R \sim 1.25$ . Objects spectra with known features of water ice, methane, methanol, and featureless spectra, are coded using colors as described in the legend. There is no obvious/clear connection between  $B - R$  colors and the presence of spectral features.

bility (risk) we are willing to take in rejecting the null hypothesis  $H_0$  (*i.e.* to claim no evidence for bimodality) when it is actually true (*i.e.* data is truly bimodal/multimodal) — also called type I error probability. Such value is often a source of debate, as the theories of hypotheses testing themselves (*e.g.* Lehmann 1993). The decision relies mostly whether the effects of a right or

wrong decision are of practical importance or consequence. The paradigm is: by diminishing the probability of wrongly reject a null hypothesis (*e.g.* decide for bimodality when bimodality was not present in the parent population) we increase the probability of wrongly accepting the null hypothesis (*i.e.* deciding for unimodality when bimodality was in fact present), also called type II error probability, or risk factor  $\beta$ . Some authors and/or research fields, consider that there is only sufficient evidence against  $H_0$  when the achieved significance level is  $SL < 0.3\%$ , *i.e.* using  $\alpha = 0.3\%$  (the  $3\sigma$  Gaussian probability), others require even  $\alpha = 0.0003\%$  ( $6\sigma$ ). Such might be a criterion for rejection of  $H_0$  but not a very useful ‘rating’ for the evidence against  $H_0$ , which is what we are implicitly doing. We rate the evidence against  $H_0$  following a most common procedure in Statistics:  $SL < 5\%$  — reasonably strong evidence against  $H_0$ ,  $SL < 2.5\%$  — strong evidence against  $H_0$ , and  $SL < 1\%$  — very strong evidence against  $H_0$  (*e.g.* Efron & Tibshirani 1993), adding also the common procedure in Physics:  $SL < 0.3\%$  — clear evidence against  $H_0$ . Further, for better readability, throughout this work we may employ the abuse of language ‘evidence for bimodality’ instead of the statistically correct term ‘evidence against unimodality’.

Using the R software’s (version 2.14.1; R Development Core Team 2011) Dip Test package (Hartigan 1985; Hartigan & Hartigan 1985; Maechler 2011) we test the null hypothesis  $H_0$ : ‘the sample is consistent with an unimodal parent distribution’ over all objects in the  $B - R$  vs.  $H_R(\alpha)$  space, against the alternative hypothesis  $H_1$ : ‘the sample is not consistent with an unimodal parent distribution’ (hence it is bimodal or multimodal). The full sample, in spite of the apparent two spikes, shows no relevant evidence against color unimodality, neither with ( $n = 253$ ,  $SL = 17\%$ ) nor without ( $n = 224$ ,  $SL = 41\%$ ) Centaurs (see Fig. 2 a). The Centaur population ( $n = 29$ ) shows strong evidence against unimodality at 1.6%. Removing the 3 brightest Centaurs (with  $H_R(\alpha) \gtrsim 6.6$ ) improves the significance to 0.3%. To refine the analysis and test different ranges in  $H_R(\alpha)$  we ran the Dip Test on sub-samples using a running cutoff in  $H_R(\alpha)$  that was shifted by 0.1 mag between consecutive tests.

**Bimodal distribution of ‘small’ objects:** We performed iterative Dip Tests with a  $H_{R,cut}$  starting at the maximum  $H_R(\alpha)$  value, and decreasing in steps of 0.1 mag; in each iteration we run the test on those objects above the cutoff line (*i.e.* with  $H_R(\alpha) \geq H_{R,cut}$ ). We stop shifting  $H_{R,cut}$  when we detect the maximum of evidence against unimodality (*i.e.* a minimum of significance level, henceforth accepting the alternate hypothesis ‘the distribution is bimodal/multimodal’) Evidence for bimodality at significance levels better than 5% start to be seen for objects with  $H_R(\alpha) \geq 7.1$ . This evidence peaks at a significance of 0.1% for the 124 faint objects with  $H_R(\alpha) \geq 6.8$ .

We propose that the visible surface color distribution of (non-active) icy bodies of the outer Solar System depends only on objects size, and is independent of their dynamical classification. No mechanism has yet been found to explain the color bimodality only for Centaurs. However, since such mechanism might exist even if not yet found, we re-analyze the sample removing the Centaurs. Naturally, the sampling of the smaller objects diminishes considerably, hence reducing the statistical significance against the null hypothesis (*i.e.* increases the probability of observing two groups on a purely random distribution of colors). Nonetheless, the 98 remaining objects with  $H_R(\alpha) \geq 6.8$  show evidence for bimodality at a significance level of 3.5%, reaching a significance minimum of 1.8% for the 165 objects

with  $H_R(\alpha) \geq 5.8$ . In both cases the ‘gap’ is centered around  $B - R \sim 1.60$  (see Figs. 1 and 2 b).

**Bimodal distribution of ‘large’ objects:** We test the brightest part of the sample using a cutoff limit starting at the minimum  $H_R(\alpha)$  value; we consider objects below the cutoff (*i.e.* brighter than  $H_{R,cut}$ ) and shift it up in steps of 0.1 mag. We find very strong evidence against unimodality for objects with  $H_R(\alpha) \lesssim 5.0$  ( $SL = 0.9\%$ ). Data still shows reasonably strong evidence against unimodality for objects up to  $H_R(\alpha) \lesssim 5.6$ . The ‘gap’ is located at  $B - R \sim 1.25$ . There are no Centaurs in this brightness range. Explicitly, evidence for ‘large’ objects bimodality has not been previously reported. (see Figs. 1 and 2 c). Removing from the sample the 7 objects belonging to the ‘Haumea collisional family’ (Brown et al. 2007b; Snodgrass et al. 2010), all clustered on the lower left ‘leg’ of the  $N$  shape, erases the statistical evidence against the null hypothesis, even if still suggestive to the eye. Therefore, with the present data sample, the ‘evidence for bimodality’ among bright KBOs cannot be stated as independent from the peculiar properties of the Haumea collisional family.

**The ‘intermediate’ size continuum:** The 91 objects with  $6.8 > H_R(\alpha) > 5.0$ , which include 3 Centaurs, do not show evidence against a unimodal behavior ( $SL = 98.0\%$ ) even if a small gap seems suggestive to the eye (see Figs. 1 and 2 d). However, statistically, their inclusion in the fainter group does not decrease the significance below the ‘strong evidence against unimodality’, *i.e.*  $SL = 2.5\%$  (see Figs. 1 and 2 d). On the other hand, if added to the ‘large’ objects the statistical evidence for bimodality of ‘large’ objects does not hold.

To check for the effects of non-correcting  $H_R(\alpha)$  from phase angle effects we performed Monte-Carlo simulations. First, we compute all the possible  $\alpha$  values and their probability distribution for an ‘average’ Centaur with semi-major axis  $a = 15$  AU. The maximum  $\alpha$  is  $3.8^\circ$  being the median value  $3.2^\circ$ . Analogously, we do the same for a KBO with  $a = 40$  AU. The maximum  $\alpha$  is  $1.4^\circ$  and the median value  $1.2^\circ$ . Therefore, on average, our absolute magnitudes might be *overestimated* by  $\Delta H_R \approx 0.35$ , for Centaurs, and by  $\Delta H_R \approx 0.13$ , for KBOs. Simulating 1000 ‘phase-corrected’  $H_R$  data-samples, following the probability distribution of the corresponding  $\alpha$  angles did not alter any of the results obtained using simply  $H_R(\alpha)$ .

## 6. Interpretation

Our analysis shows that the  $B - R$  colors of Centaurs and KBOs when plotted as a function of  $H_R(\alpha)$  display an N-shaped, double bimodal behavior. The color distribution seems to depend on object size (intrinsic brightness) instead of dynamical family. Using the brightness-size-albedo relation  $D_{km} = 2 \sqrt{2.24 \cdot 10^{16} \cdot 10^{0.4(H_{R\odot} - H_R)} / p_R}$ , with solar  $H_{R\odot} = -27.10$ , the main issue is to choose a canonical geometric albedo value  $p_R$ . Recent works (Stansberry et al. 2008; Santos-Sanz et al. 2012; Vilenius et al. 2012; Mommert et al. 2012) show a wide range of values, for each dynamical family, in some cases far from the 0.04 value previously assumed from comet studies. As we need only a rough estimate of size ranges, we pick the average value of  $p_R = 0.09$ . Using this parameter, objects with diameters  $165 \lesssim D_{km} \lesssim 380$  present a rather continuous range of B-R colors.

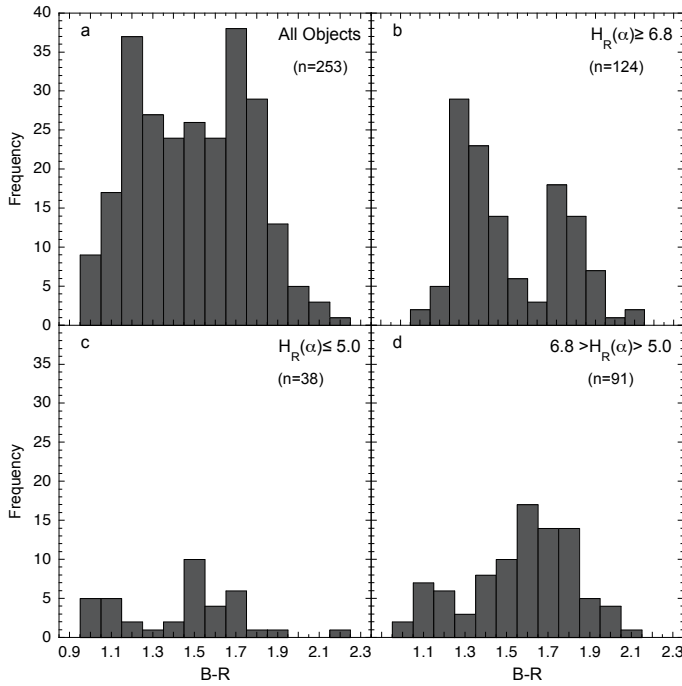


Fig. 2: Histograms of  $B - R$  colors from selected  $H_R(\alpha)$  ranges: a) All the 253 objects. Taken globally do not exhibit statistical evidence for bimodality, which was known to exist among Centaurs. b) The 124 ‘small’ objects, with  $H_R(\alpha) \geq 6.8$ . Evidence for bimodal behavior is clear and still present when removing Centaurs. c) The 38 ‘large’ objects, with  $H_R(\alpha) \leq 5.0$ . A bimodal behavior is shown but it loses the statistical significance without the ‘Haumea collisional family’ objects. d) The 91 ‘intermediate’ size objects,  $6.8 > H_R(\alpha) > 5.0$ . Regardless of the apparent small gap at  $B - R \sim 1.3$  there is no statistical evidence for two separate groups.

Visible and near-infrared (NIR) spectroscopy for about 75 bright objects (Barucci et al. 2011, for a review) also indicates that the surface compositions of KBOs and Centaurs is very diverse. The largest objects are coated in methane ice, while intermediate size objects display water-ice features, sometimes with traces of other volatiles. Small KBOs generally have featureless spectra. The presence of volatiles on the surface of an object may be related to its ability to retain them, *i.e.* to its size and temperature (Schaller & Brown 2007). It should also depend on the subsequent irradiation history (Brown et al. 2011). However no correlation can be made to date between visible colors and NIR spectral properties. For example, two objects of comparable size, Quaoar and Orcus, both exhibit water ice-dominated surfaces but have, respectively, very red and neutral visible colors (Delsanti et al. 2010).

Objects smaller than  $\sim 100$ -150 km, including most of the known Centaurs, are believed to be fragments from the collision of larger objects (Pan & Sari 2005). Predicting the properties of these fragments is a complex task, but the field shows promising advances (for a review, see Leinhardt et al. 2008). An immediate hypothesis is that red and neutral objects are the only possible outcomes of a disruptive collision. Thermal evolution modeling suggests that KBOs, especially large ones, should have a layered structure, including some liquid water leading to a complete differentiation of the object (Merk & Prialnik 2006; Guilbert-Lepoutre et al. 2011). A catastrophic collision could result in the formation of fragments with very different properties, depending on whether they come from the core of the parent body, or its mantle, or some subsurface layers. However, our current knowl-

edge of KBOs internal properties and evolution is still incipient to support or discard such an hypothesis. Besides, it is hard to understand why objects with  $B - R \sim 1.6$  (in the gap of the small object’s bimodal distribution) should be inexistent. Maybe their relative number is so small compared to the neutral and red groups that we can hardly observe them, leading to another puzzling question. Research on these aspects should be encouraged, in particular the detection and measurement of many more small objects — KBOs and Centaurs — could help further constraining their color distribution and other properties. The objects in the ‘intermediate’  $H_R(\alpha)$  range ( $6.8 > H_R(\alpha) > 5.0$ ) seem unimodally distributed in  $B - R$  color; they might represent a transition phase between the two bimodal distributions. These medium-sized objects are probably too large to be remnants from disruptive collisions, and too small to have recently undergone cryovolcanic activity (they may not even be differentiated). They might, actually, represent the only group where the outcomes of the combined effects of different birthplaces, space weathering and thermal processing can be studied or analyzed.

The evidence for bimodal distribution among the largest objects is also puzzling. These are supposedly the best studied objects, yet the evidence for a bimodal distribution of their surface colors has never been reported. Nonetheless, when removing the 7 Haumea collisional family objects from our sample it no longer provides evidence against an unimodal distribution, even if apparent to the eye. This issue should be further analyzed when larger sampling is available.

In this work, we confirm that there is no noticeable link between the surface composition of an object and its visible colors. Objects hosting water ice are distributed both among large and small objects, and among red and blue ones. When it comes to volatiles such as methane ( $\text{CH}_4$ ) or methanol ( $\text{CH}_3\text{OH}$ ), we find that they are also distributed among all groups, although they might be more difficult to detect on small/fainter objects. We nonetheless find a cluster of featureless objects among the red group of large objects: these might represent the most irradiated/oldest surfaces in the overall population. Therefore, it seems that a simple explanation such as the model of atmospheric escape proposed by Schaller & Brown (2007) might not be sufficient to explain the colors and compositions of KBOs. The reason why they evolved in two different color groups can be very complex, and should involve different thermal, collisional, irradiation histories, on top of possible different birthplaces.

## 7. Summary

In this work we analyze the  $B - R$  color distribution as a function of  $H_R(\alpha)$  magnitude for 253 Centaurs and KBOs, including 10 new measurements, and with the information on their NIR spectral features. Using the known diameters,  $D$ , and albedos,  $p_V$ , of 74 of these objects we verify that  $H_R$  and  $D$  correlate very strongly ( $\rho = -0.92^{+0.03}_{-0.02}$ ,  $SL \ll 0.01\%$ ) validating  $H_R$  as a good proxy for size. Further, through simulations, we show that not correcting  $H_R(\alpha)$  to  $H_R(\alpha = 0^\circ)$  does not change any of the global results. Our analysis shows:

1. The  $B - R$  vs.  $H_R(\alpha)$  color distribution is  $\mathcal{N}$ -shaped, evidencing that  $B - R$  colors are probably dominated by a size effect independent from dynamical classification.
2. Small objects, including both KBOs and Centaurs, display a bimodal structure of  $B - R$  colors at 0.1% significance level (*i.e.* objects with  $H_R(\alpha) \geq 6.8$ , or  $D_{km} \lesssim 165$ , assuming  $p_R = 0.09$ ) with the ‘gap’ centered at  $B - R \sim 1.60$ . Removing Centaurs from the sample reduces greatly the

sampling on small objects reducing also the significance of the result to 3.8%.

3. Large objects evidence also for a bimodal structure, with minimum significance of 0.9%, for  $H_R(\alpha) \lesssim 5.0$  ( $D_{km} \gtrsim 380$ , assuming  $p_R = 0.09$ ), and color ‘gap’ centered at  $B - R \sim 1.25$ . Reasonable evidence for this bimodality starts when considering only objects with  $H_R(\alpha) \lesssim 5.6$  ( $D_{km} \gtrsim 290$ ) dropping below the critical 5% when reaching  $H_R(\alpha) \lesssim 4.4$  ( $D_{km} \gtrsim 500$ ). However, this behavior seems dominated by the presence of 7 Haumea collisional family objects which ‘cluster’ at the lower left leg of the  $\mathcal{N}$ -shape. Once removed, there is no statistical evidence against compatibility with a random unimodal distribution for the larger KBOs.
4. Intermediate sized objects do not show incompatibility with a continuum of  $B - R$  colors (*i.e.*  $6.8 > H_R(\alpha) > 5.0$ , or  $165 \lesssim D_{km} \lesssim 380$ , assuming  $p_R = 0.09$ ). These objects seem too large to be remnants from disruptive collisions and too small to hold cryovolcanic activity. They might be the best targets to study the combined effects of different birth-places, different space weathering, and different thermal processing. Further studies are encouraged.
5. Inspecting the NIR spectral properties against  $B - R$  colors shows no obvious link between the colors and the chemical composition of the objects’ surfaces.

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## References

- Barkume, K. M., Brown, M. E., & Schaller, E. L. 2008, *AJ*, 135, 55
- Barucci, M., Alvarez-Candal, A., Merlin, F., et al. 2011, *Icarus*, 214, 297
- Barucci, M. A., Doressoundiram, A., Tholen, D., Fulchignoni, M., & Lazzarin, M. 1999, *Icarus*, 142, 476
- Barucci, M. A., Morea Dalle Ore, C., Alvarez-Candal, A., et al. 2010, *AJ*, 140, 2095
- Barucci, M. A., Romon, J., Doressoundiram, A., & Tholen, D. J. 2000, *Astron. J.*, 120, 496
- Belskaya, I. N., Levasseur-Regourd, A.-C., Shkuratov, Y. G., & Muinonen, K. 2008, Surface Properties of Kuiper Belt Objects and Centaurs from Photometry and Polarimetry, ed. Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A., & Dotson, R., 115–127
- Boehnhardt, H., Delsanti, A., Barucci, A., et al. 2002, *A&A*, 395, 297
- Boehnhardt, H., Tozzi, G. P., Birkle, K., et al. 2001, *A&A*, 378, 653
- Brown, M. E., Barkume, K. M., Blake, G. A., et al. 2007a, *AJ*, 133, 284
- Brown, M. E., Barkume, K. M., Ragozzine, D., & Schaller, E. L. 2007b, *Nature*, 446, 294
- Brown, M. E., Schaller, E. L., & Fraser, W. C. 2011, *ApJ*, 739, L60
- Brown, R. H., Cruikshank, D. P., & Pendleton, Y. 1999, *ApJ*, 519, L101
- Cruikshank, D. P., Roush, T. L., Bartholomew, M. J., et al. 1998, *Icarus*, 135, 389
- Delsanti, A., Hainaut, O., Jourdeuil, E., et al. 2004, *A&A*, 417, 1145
- Delsanti, A., Merlin, F., Guilbert-Lepoutre, A., et al. 2010, *A&A*, 520, A40
- Delsanti, A. C., Boehnhardt, H., Barrera, L., et al. 2001, *A&A*, 380, 347
- DeMeo, F. E., Barucci, M. A., Merlin, F., et al. 2010, *A&A*, 521, A35
- Doressoundiram, A., Barucci, M. A., Romon, J., & Veillet, C. 2001, *Icarus*, 154, 277
- Doressoundiram, A., Barucci, M. A., Tozzi, G. P., et al. 2005a, *Planet. Space Sci.*, 53, 1501
- Doressoundiram, A., Peixinho, N., de Bergh, C., et al. 2002, *AJ*, 124, 2279
- Doressoundiram, A., Peixinho, N., Doucet, C., et al. 2005b, *Icarus*, 174, 90
- Doressoundiram, A., Peixinho, N., Moullet, A., et al. 2007, *AJ*, 134, 2186
- Dotto, E., Barucci, M. A., Boehnhardt, H., et al. 2003, *Icarus*, 162, 408
- Efron, B. & Tibshirani, R. J. 1993, *An Introduction to the Bootstrap* (Chapman & Hall/CRC)
- Fernandez, J. A. 1980, *MNRAS*, 192, 481
- Ferrin, I., Rabinowitz, D., Schaefer, B., et al. 2001, *ApJ*, 548, L243
- Fornasier, S., Doressoundiram, A., Tozzi, G. P., et al. 2004, *A&A*, 421, 353
- Gil-Hutton, R. 2002, *Planet. Space Sci.*, 50, 57
- Gladman, B., Marsden, B. G., & Vanlaerhoven, C. 2008, *Nomenclature in the Outer Solar System*, ed. Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A., & Dotson, R., 43–57
- Green, S. F., McBride, N., O’Ceallaigh, D. P., et al. 1997, *MNRAS*, 290, 186
- Grundy, W. M. 2009, *Icarus*, 199, 560
- Grundy, W. M., Buie, M. W., & Spencer, J. R. 2005, *AJ*, 130, 1299
- Guilbert, A., Alvarez-Candal, A., Merlin, F., et al. 2009a, *Icarus*, 201, 272
- Guilbert, A., Barucci, M. A., Brunetto, R., et al. 2009b, *A&A*, 501, 777
- Guilbert-Lepoutre, A., Lasue, J., Federico, C., et al. 2011, *A&A*, 529, A71
- Gulbis, A. A. S., Elliot, J. L., & Kane, J. F. 2006, *Icarus*, 183, 168
- Hainaut, O. R., Delahodde, C. E., Boehnhardt, H., et al. 2000, *A&A*, 356, 1076
- Hainaut, O. R. & Delsanti, A. C. 2002, *A&A*, 389, 641
- Hartigan, J. A. & Hartigan, P. M. 1985, *Ann. Stat.*, 13, 70
- Hartigan, P. M. 1985, *Appl. Stat.*, 34, 320
- Horner, J., Evans, N. W., & Bailey, M. E. 2004, *MNRAS*, 354, 798
- Horner, J. & Lykawka, P. S. 2010, *MNRAS*, 402, 13
- Jewitt, D. & Luu, J. 1993, *Nature*, 362, 730
- Jewitt, D. & Luu, J. 1998, *AJ*, 115, 1667
- Jewitt, D. C. 2002, *AJ*, 123, 1039
- Jewitt, D. C. & Luu, J. X. 2001, *AJ*, 122, 2099
- Kashikawa, N., Aoki, K., Asai, R., et al. 2002, *PASJ*, 54, 819
- Kern, S. D., McCarthy, D. W., Buie, M. W., et al. 2000, *ApJ*, 542, L155
- Kowal, C. T., Liller, W., & Chaisson, L. J. 1977, *IAU Circ.*, 3147, 1
- Krisciunas, K., Sinton, W., Tholen, K., et al. 1987, *PASP*, 99, 887
- Lacerda, P., Jewitt, D., & Peixinho, N. 2008, *AJ*, 135, 1749
- Landolt, A. U. 1992, *AJ*, 104, 340
- Lazzaro, D., Florczak, M. A., Angeli, C. A., et al. 1997, *Planet. Space Sci.*, 45, 1607
- Lehmann, E. L. 1993, *Journal of the American Statistical Association*, 88, 1242
- Leinhardt, Z. M., Stewart, S. T., & Schultz, P. H. 2008, *Physical Effects of Collisions in the Kuiper Belt*, ed. Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A., & Dotson, R., 195–211
- Levison, H. F. & Duncan, M. J. 1997, *Icarus*, 127, 13
- Luu, J. & Jewitt, D. 1996, *AJ*, 112, 2310
- Lykawka, P. S. & Mukai, T. 2007, *Icarus*, 189, 213
- Maechler, M. 2011, *Diptest: Hartigan’s dip test statistic for unimodality - corrected code*, r package version 0.75-1
- Merk, R. & Pralnik, D. 2006, *Icarus*, 183, 283
- Merlin, F., Alvarez-Candal, A., Delsanti, A., et al. 2009, *AJ*, 137, 315
- Mommert, M., Harris, A. W., Kiss, C., et al. 2012, *A&A*, (in press)
- Pan, M. & Sari, R. 2005, *Icarus*, 173, 342
- Peixinho, N., Boehnhardt, H., Belskaya, I., et al. 2004, *Icarus*, 170, 153
- Peixinho, N., Doressoundiram, A., Delsanti, A., et al. 2003, *A&A*, 410, L29
- Peixinho, N., Lacerda, P., Ortiz, J. L., et al. 2001, *A&A*, 371, 753
- Pinilla-Alonso, N., Brunetto, R., Licandro, J., et al. 2009, *A&A*, 496, 547
- R Development Core Team. 2011, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0
- Rabinowitz, D. L., Barkume, K., Brown, M. E., et al. 2006, *ApJ*, 639, 1238
- Rabinowitz, D. L., Schaefer, B. E., Schaefer, M., & Tourtellotte, S. W. 2008, *AJ*, 136, 1502
- Rabinowitz, D. L., Schaefer, B. E., & Tourtellotte, S. W. 2007, *AJ*, 133, 26
- Romanishin, W., Tegler, S. C., & Consolmagno, G. J. 2010, *AJ*, 140, 29
- Romanishin, W., Tegler, S. C., Levine, J., & Butler, N. 1997, *AJ*, 113, 1893
- Romon-Martin, J., Barucci, M. A., de Bergh, C., et al. 2002, *Icarus*, 160, 59
- Romon-Martin, J., Delahodde, C., Barucci, M. A., de Bergh, C., & Peixinho, N. 2003, *A&A*, 400, 369
- Santos-Sanz, P., Lellouch, E., Fornasier, S., et al. 2012, *A&A*, (in press)
- Santos-Sanz, P., Ortiz, J. L., Barrera, L., & Boehnhardt, H. 2009, *A&A*, 494, 693
- Schaller, E. L. & Brown, M. E. 2007, *ApJ*, 659, L61
- Schaller, E. L. & Brown, M. E. 2008, *ApJ*, 684, L107
- Sheppard, S. S. 2010, *AJ*, 139, 1394
- Sheppard, S. S. & Trujillo, C. A. 2006, *Science*, 313, 511
- Snodgrass, C., Carry, B., Dumas, C., & Hainaut, O. 2010, *A&A*, 511, A72
- Stansberry, J., Grundy, W., Brown, M., et al. 2008, *Physical Properties of Kuiper Belt and Centaur Objects: Constraints from the Spitzer Space Telescope*, ed. Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A., & Dotson, R., 161–179
- Tegler, S. C., Bauer, J. M., Romanishin, W., & Peixinho, N. 2008, *Colors of Centaurs*, ed. Barucci, M. A., Boehnhardt, H., Cruikshank, D. P., Morbidelli, A., & Dotson, R., 105–114
- Tegler, S. C. & Romanishin, W. 1997, *Icarus*, 126, 212
- Tegler, S. C. & Romanishin, W. 1998, *Nature*, 392, 49
- Tegler, S. C. & Romanishin, W. 2000, *Nature*, 407, 979



Tegler, S. C. & Romanishin, W. 2003, *Icarus*, 161, 181  
Tegler, S. C., Romanishin, W., & Consolmagno, G. J. 2003, *ApJ*, 599, L49  
Thébault, P. & Doressoundiram, A. 2003, *Icarus*, 162, 27  
Thompson, W. R., Murray, B. G. J. P. T., Khare, B. N., & Sagan, C. 1987, *J. Geophys. Res.*, 92, 14933  
Trujillo, C. A. & Brown, M. E. 2002, *ApJ*, 566, L125  
Vilenius, E., Kiss, C., Mommert, M., et al. 2012, *A&A*, (in press)  
Volk, K. & Malhotra, R. 2008, *ApJ*, 687, 714  
Yu, Q. & Tremaine, S. 1999, *Astrophys. J.*, 118, 1873

## Appendix A: Compiled Database

For each object, we compute the average color index from the different papers from data obtained *simultaneously* in B and R bands (*e.g.* contiguous observations within a same night). When individual R apparent magnitude and date is available, we compute the  $H_R(\alpha) = R - 5 \log(r \cdot \Delta)$ , where  $R$  is the R-band magnitude,  $r$  and  $\Delta$  are the helio- and geocentric distances at the time of observation in AU, respectively. When  $V$  and  $V - R$  color is available, we derive an  $R$  and then  $H_R(\alpha)$  value. We do not correct for the phase angle  $\alpha$  effect as we need only a general estimation of the absolute magnitude for our complete sample. In addition, few objects have phase correction coefficient available in the literature, and no universally accepted canonical values per dynamical class can be strictly adopted. Table A.1 presents the resulting values. This table includes also spectral information on the presence of water ice, methanol, methane, or confirmed featureless spectra, as available in the literature. We highlight only the cases with clear bands on the spectrum which were reported/confirmed by some other work.

There is no strict definition for the dynamical classes of Centaurs and KBOs. Roughly speaking: objects orbiting in mean motion resonances with Neptune are called ‘resonants’ (if located in the 1:1 resonance are also known as Neptune Trojans, and known as Plutinos if located in the 3:2 resonance); Centaurs are the objects with orbits between those of Jupiter and Neptune; Scattered Disk Objects (SDOs), are those within probable gravitational influence of Neptune; Detached KBOs, are those beyond past or future gravitational influence by Neptune; Classical KBOs, are those with rather circular orbits beyond Neptune and below the 2:1 resonance region (being called Hot if their orbital inclination is higher than  $5^\circ$  or Cold if lower).

To determine the dynamical class we first gathered the orbital elements, with epoch 2011–12–05, from ‘The Asteroid Orbital Elements Database’, *astorb.dat*<sup>1</sup>, maintained by the ‘Lowell Observatory’ based on astrometric observations by the ‘Minor Planet Center’. Then, using the particular classification scheme suggested by Lykawka & Mukai (2007), including their analysis of objects located in the mean motion resonances (MMR) with Neptune, dynamical class was determined following a 11 steps algorithm:

1.  $q < a_J \Rightarrow$  Not analysed
2. in 1 : 1 MMR with Neptune  $\Rightarrow$  Neptune Trojan
3. in 3 : 2 MMR with Neptune  $\Rightarrow$  Plutino
4. in other MMR with Neptune  $\Rightarrow$  Other Resonant
5.  $q > a_J \wedge a < a_N \Rightarrow$  Centaur
6.  $a_J < q < a_N \wedge a \geq a_N \Rightarrow$  Scattered Disk Object (SDO)
7.  $a_N < q \leq 37 \text{ AU} \Rightarrow$  Scattered Disk Object (SDO)
8.  $q \geq 40 \text{ AU} \wedge a \geq 48 \text{ AU} \Rightarrow$  Detached KBO (DKBO)
9.  $37 \text{ AU} \leq q \leq 40 \text{ AU} \Rightarrow$  Scattered or Detached KBO (SDKBO)

10.  $i < 5^\circ \wedge \{ [q \geq 37 \text{ AU} \wedge (37 \text{ AU} \leq a \leq 40 \text{ AU})] \vee [q \geq 38 \text{ AU} \wedge (42 \text{ AU} \leq a \leq 48 \text{ AU})] \} \Rightarrow$  Cold Classical KBO (cCKBO)
11.  $i \geq 5^\circ \wedge q \geq 37 \text{ AU} \wedge (37 \text{ AU} \leq a \leq 48 \text{ AU}) \Rightarrow$  Hot Classical KBO (hCKBO)

being  $q$  and  $a$  the object’s perihelion and semi-major axis, respectively. Jupiter semi-major axis is  $a_J$ , and Neptune’s is  $a_N$ . Note that throughout the algorithm an object can be reclassified.

We are aware that there are more complex classification schemes, which may be more refined, but the boundaries between families do not change significantly. We chose this one for its computational simplicity.

References for the colors presented in Table A.1 are : (1) Luu & Jewitt (1996); (2) Lazzaro et al. (1997); (3) Romon-Martin et al. (2003); (4) Romanishin et al. (1997); (5) Romon-Martin et al. (2002); (6) Tegler & Romanishin (1998); (7) Jewitt & Luu (2001); (8) Doressoundiram et al. (2002); (9) Tegler & Romanishin (2000); (10) Delsanti et al. (2001); (11) Tegler & Romanishin (1997); (12) Jewitt & Luu (1998); (13) Barucci et al. (1999); (14) Boehnhardt et al. (2001); (15) Doressoundiram et al. (2007); (16) Doressoundiram et al. (2001); (17) Green et al. (1997); (18) Boehnhardt et al. (2002); (19) Tegler & Romanishin (2003); (20) Hainaut et al. (2000); (21) Sheppard (2010); (22) Barucci et al. (2000); (23) Rabinowitz et al. (2008); (24) Tegler et al. <http://www.physics.nau.edu/teglar/research/survey.htm>; (25) Tegler et al. (2003); (26) Peixinho et al. (2001); (27) Trujillo & Brown (2002); (28) Peixinho et al. (2004); (29) Ferrin et al. (2001); (30) Doressoundiram et al. (2005b); (31) Santos-Sanz et al. (2009); (32) Dotto et al. (2003); (33) Fornasier et al. (2004); (34) Doressoundiram et al. (2005a); (35) Gulbis et al. (2006); (36) Rabinowitz et al. (2007); (37) Romanishin et al. (2010); (38) Rabinowitz et al. (2006); (39) Lacerda et al. (2008); (40) Snodgrass et al. (2010); (41) Sheppard & Trujillo (2006).

References for the spectral features indicated in Table A.1 are: (a) Romon-Martin et al. (2003); (b) Cruikshank et al. (1998); (c) Kern et al. (2000); (d) Guilbert et al. (2009b); (e) Jewitt & Luu (2001); (f) Brown et al. (1999); (g) Barkume et al. (2008); (h) Guilbert et al. (2009a); (i) Barucci et al. (2011); (j) DeMeo et al. (2010); (k) Grundy et al. (2005); (l) Barucci et al. (2010); (m) Delsanti et al. (2010); (n) Pinilla-Alonso et al. (2009); (o) Merlin et al. (2009); (p) Brown et al. (2007a); (q) Schaller & Brown (2008).

<sup>1</sup> <ftp://ftp.lowell.edu/pub/elgb/astorb.dat.gz>

**Table A.1.** Compilation of absolute magnitude  $H_R(\alpha)$ ,  $B - R$  colors, and spectral features used in this work

Object	Dynamical Class	$H_R(\alpha)$	$B - R$	Spectral features	References
(2060) Chiron	Centaur	6.287±0.022	1.010±0.044	Water ice	1, 2, 3, a
(5145) Pholus	Centaur	7.198±0.056	1.970±0.108	Methanol	4, b
(7066) Nessus	Centaur	9.020±0.068	1.847±0.165		1
(8405) Asbolus	Centaur	9.257±0.120	1.228±0.057	Water ice	4, 5, c
(10199) Chariklo	Centaur	6.569±0.015	1.299±0.065	Water ice	6, 7, d
(10370) Hylonome	Centaur	9.250±0.131	1.153±0.081		1, 6, 8
(15760) 1992 QB <sub>1</sub>	Cold Classical	6.867±0.121	1.670±0.145		1, 7, 9
(15788) 1993 SB	Plutino	8.032±0.122	1.276±0.100		7, 9, 10
(15789) 1993 SC	Plutino	6.722±0.074	1.720±0.140	Methane	1, 7, 11, 12, e
(15810) 1994 JR <sub>1</sub>	Plutino	6.867±0.077	1.610±0.216		13
(15820) 1994 TB	Plutino	7.527±0.091	1.759±0.155		1, 7, 10, 11, 13
(15874) 1996 TL <sub>66</sub>	Scattered Disk Object	5.131±0.144	1.113±0.070		6, 7, 12, 13, 14
(15875) 1996 TP <sub>66</sub>	Plutino	6.953±0.071	1.678±0.123		6, 7, 12, 13, 14, 15
(15883) 1997 CR <sub>29</sub>	Scattered Disk Object	7.076±0.135	1.260±0.128		7, 16
(16684) 1994 JQ <sub>1</sub>	Cold Classical	6.618±0.117	1.738±0.120		17, 18, 19
(19255) 1994 VK <sub>8</sub>	Cold Classical	7.016±0.163	1.680±0.067		9
(19299) 1996 SZ <sub>4</sub>	Plutino	8.184±0.159	1.299±0.102		7, 9, 18
(19308) 1996 TO <sub>66</sub>	Resonant (19:11)	4.530±0.044	1.056±0.210	Water ice	6, 7, 12, 13, 14, 20, 21, f
(19521) Chaos	Hot Classical	4.442±0.069	1.558±0.062		8, 9, 10, 22
(20000) Varuna	Hot Classical	3.345±0.059	1.530±0.036	Water ice	8, g
(20108) 1995 QZ <sub>9</sub>	Plutino	7.889±0.399	1.400±0.050		9, This work
(24835) 1995 SM <sub>55</sub>	Hot Classical	4.352±0.040	1.018±0.052	Water ice	8, 10, 14, 23, g
(24952) 1997 QJ <sub>4</sub>	Plutino	7.389±0.114	1.104±0.104		7, 18
(24978) 1998 HJ <sub>151</sub>	Cold Classical	7.008±0.050	1.820±0.042		19
(26181) 1996 GQ <sub>21</sub>	Resonant (11:2)	4.467±0.090	1.693±0.079	Methanol	18, 24, g
(26308) 1998 SM <sub>165</sub>	Resonant (2:1)	5.757±0.119	1.620±0.105		9, 10, 15
(26375) 1999 DE <sub>9</sub>	Resonant (5:2)	4.810±0.046	1.536±0.056	Featureless	7, 8, 25, h
(28978) Ixion	Scattered Disk Object	3.366±0.038	1.634±0.035	Water ice	8, h
(29981) 1999 TD <sub>10</sub>	Scattered Disk Object	8.698±0.038	1.230±0.028	Water ice	8, g
(31824) Elatus	Centaur	10.439±0.107	1.672±0.071	Water ice	8, 10, 26, g
(32532) Thereus	Centaur	9.365±0.038	1.190±0.032	Water ice	25, h
(32929) 1995 QY <sub>9</sub>	Plutino	7.489±0.126	1.160±0.150		1, 13
(33001) 1997 CU <sub>29</sub>	Cold Classical	6.173±0.078	1.804±0.115		7, 16, 22, 27
(33128) 1998 BU <sub>48</sub>	Scattered Disk Object	6.889±0.127	1.692±0.089		8, 10
(33340) 1998 VG <sub>44</sub>	Plutino	6.292±0.077	1.511±0.055		8, 14, 16, 24
(35671) 1998 SN <sub>165</sub>	Scattered Disk Object	5.431±0.068	1.123±0.082		7, 10, 16
(38083) Rhadamanthus	Scattered Disk Object	7.432±0.063	1.177±0.109		18
(38084) 1999 HB <sub>12</sub>	Resonant (5:2)	6.718±0.050	1.409±0.049		16, 25, 27, 28
(38628) Huya	Plutino	4.674±0.099	1.539±0.062	Featureless	29, 7, 16, 18, g
(40314) 1999 KR <sub>16</sub>	Scattered Disk Object	5.527±0.039	1.872±0.068		7, 18, 27
(42301) 2001 UR <sub>163</sub>	Resonant (9:4)	3.812±0.109	2.190±0.130	Featureless	15, 30, 31, g
(42355) Typhon	Scattered Disk Object	7.358±0.076	1.292±0.071	Water ice	25, 28, h
(44594) 1999 OX <sub>3</sub>	Scattered Disk Object	6.835±0.078	1.839±0.087	Water ice	8, 9, 10, 15, 21, 30, i
(47171) 1999 TC <sub>36</sub>	Plutino	4.851±0.054	1.740±0.049	Water ice	10, 16, 25, 32, h
(47932) 2000 GN <sub>171</sub>	Plutino	5.666±0.090	1.559±0.066	Featureless	18, 24, h
(48639) 1995 TL <sub>8</sub>	Detached KBO	4.667±0.091	1.693±0.217		8, 10, 21
(49036) Pelion	Centaur	10.157±0.112	1.248±0.096		9, 18
(50000) Quaoar	Hot Classical	2.220±0.029	1.588±0.021	Methane	25, 33, h
(52747) 1998 HM <sub>151</sub>	Cold Classical	7.417±0.100	1.550±0.103		19
(52872) Okyrhoe	Centaur	10.775±0.078	1.237±0.086	Water ice	10, 16, 32, g
(52975) Cyllarus	Centaur	8.634±0.101	1.803±0.102		8, 10, 14, 25
(53311) Deucalion	Cold Classical	6.662±0.060	2.030±0.160		27
(54598) Bienor	Centaur	7.727±0.077	1.158±0.075	Methanol	8, 10, 15, h
(55565) 2002 AW <sub>197</sub>	Hot Classical	3.156±0.059	1.498±0.044	Featureless	24, 33, 34, h
(55576) Amycus	Centaur	7.789±0.042	1.814±0.044	Water ic	24, 28, 33, 34, i
(55636) 2002 TX <sub>300</sub>	Hot Classical	3.296±0.047	1.010±0.028	Water ice	25, 30, q
(55637) 2002 UX <sub>25</sub>	Scattered Disk Object	3.486±0.084	1.502±0.052	Water ice	24, 31, g
(55638) 2002 VE <sub>95</sub>	Plutino	5.143±0.062	1.790±0.040	Methanol	24, g
(58534) Logos	Cold Classical	6.759±0.181	1.653±0.150		7, 22
(59358) 1999 CL <sub>158</sub>	Scattered Disk Object	6.653±0.090	1.190±0.072		8

**References:** see Appendix A



Table A.1 cont'd

Object	Dynamical Class	$H_R(\alpha)$	$B - R$	Spectral features	References
(60454) 2000 CH <sub>105</sub>	Cold Classical	6.363±0.077	1.699±0.083		28
(60458) 2000 CM <sub>114</sub>	Scattered Disk Object	6.954±0.044	1.240±0.040		25
(60558) Echeclus	Centaur	9.669±0.090	1.376±0.072		18, 24
(60608) 2000 EE <sub>173</sub>	Scattered Disk Object	8.028±0.107	1.164±0.032		18, 25
(60620) 2000 FD <sub>8</sub>	Resonant (7:4)	6.344±0.061	1.806±0.113		18, 28
(60621) 2000 FE <sub>8</sub>	Resonant (5:2)	6.510±0.062	1.230±0.027		8, 25
(63252) 2001 BL <sub>41</sub>	Centaur	11.273±0.065	1.199±0.045		25, 28
(65489) Ceto	Scattered Disk Object	6.205±0.060	1.420±0.040	Water ice	25, g
(66452) 1999 OF <sub>4</sub>	Cold Classical	6.255±0.090	1.830±0.095		28
(66652) Borasisi	Cold Classical	5.420±0.051	1.610±0.050		16, 35
(69986) 1998 WW <sub>24</sub>	Plutino	7.964±0.096	1.235±0.152		8, 28
(69988) 1998 WA <sub>31</sub>	Resonant (5:2)	7.303±0.149	1.412±0.127		28
(69990) 1998 WU <sub>31</sub>	Plutino	7.988±0.200	1.225±0.086		28
(73480) 2002 PN <sub>34</sub>	Scattered Disk Object	8.487±0.046	1.280±0.020	Water ice	25, j
(79360) 1997 CS <sub>29</sub>	Cold Classical	5.068±0.085	1.746±0.077	Featureless	6, 7, 14, 22, k
(79978) 1999 CC <sub>158</sub>	Resonant (12:5)	5.409±0.091	1.566±0.100		8, 10, 24
(79983) 1999 DF <sub>9</sub>	Hot Classical	5.797±0.110	1.630±0.078		8
(80806) 2000 CM <sub>105</sub>	Cold Classical	6.302±0.030	1.980±0.230		27
(82075) 2000 YW <sub>134</sub>	Resonant (8:3)	4.429±0.064	1.417±0.077		21, 25, 28, 30, 31
(82155) 2001 FZ <sub>173</sub>	Scattered Disk Object	5.811±0.027	1.418±0.030		25, 28
(82158) 2001 FP <sub>185</sub>	Scattered Disk Object	5.940±0.053	1.402±0.055		25, 30
(83982) Crantor	Centaur	8.693±0.057	1.864±0.044	Methanol	25, 28, 33, 34, h
(84522) 2002 TC <sub>302</sub>	Scattered or Detached KBO	3.682±0.067	1.741±0.048	Water ice	21, 24, 31, g
(84719) 2002 VR <sub>128</sub>	Plutino	5.005±0.040	1.540±0.040		24
(84922) 2003 VS <sub>2</sub>	Plutino	3.794±0.070	1.520±0.030	Water ice	24, g
(85633) 1998 KR <sub>65</sub>	Cold Classical	6.599±0.073	1.727±0.144		18, 19
(86047) 1999 OY <sub>3</sub>	Scattered Disk Object	6.293±0.055	1.055±0.050		8, 9, 18
(86177) 1999 RY <sub>215</sub>	Scattered Disk Object	6.736±0.114	1.151±0.183		16, 18
(87269) 2000 OO <sub>67</sub>	Scattered Disk Object	9.057±0.170	1.702±0.092		21, 25
(87555) 2000 QB <sub>243</sub>	Scattered Disk Object	8.439±0.119	1.088±0.094		15, 28
(88269) 2001 KF <sub>77</sub>	Centaur	10.038±0.020	1.810±0.040		25
(90377) Sedna	Detached KBO	1.120±0.088	1.874±0.115	Methane	21, 24, 36, l
(90482) Orcus	Scattered Disk Object	1.991±0.054	1.042±0.037	Methane	24, 36, m
(90568) 2004 GV <sub>9</sub>	Hot Classical	3.786±0.080	1.470±0.040	Featureless	24, h
(91133) 1998 HK <sub>151</sub>	Plutino	6.937±0.076	1.240±0.064		8, 16
(91205) 1998 US <sub>43</sub>	Plutino	7.852±0.050	1.185±0.102		28
(91554) 1999 RZ <sub>215</sub>	Scattered Disk Object	8.072±0.079	1.346±0.132		18
(95626) 2002 GZ <sub>32</sub>	Centaur	6.603±0.131	1.199±0.075		25, 30, 33
(118228) 1996 TQ <sub>66</sub>	Plutino	7.245±0.195	1.881±0.144		6, 7
(118378) 1999 HT <sub>11</sub>	Resonant (7:4)	6.906±0.040	1.830±0.100		27
(118379) 1999 HC <sub>12</sub>	Scattered Disk Object	7.611±0.170	1.384±0.214		18
(118702) 2000 OM <sub>67</sub>	Scattered or Detached KBO	7.075±0.036	1.290±0.040		21
(119068) 2001 KC <sub>77</sub>	Resonant (5:2)	6.822±0.030	1.470±0.010		25
(119070) 2001 KP <sub>77</sub>	Resonant (7:4)	6.873±0.305	1.720±0.319		28, 30
(119315) 2001 SQ <sub>73</sub>	Centaur	8.857±0.069	1.130±0.020		25, 31
(119473) 2001 UO <sub>18</sub>	Plutino	7.804±0.506	2.079±0.376		30
(119878) 2002 CY <sub>224</sub>	Resonant (12:5)	5.871±0.056	1.680±0.100		31
(119951) 2002 KX <sub>14</sub>	Scattered Disk Object	4.349±0.124	1.660±0.040	Featureless	24, 37, h
(120061) 2003 CO <sub>1</sub>	Centaur	9.134±0.140	1.240±0.040		25, 27
(120132) 2003 FY <sub>128</sub>	Scattered Disk Object	4.486±0.053	1.650±0.020	Water ice	21, g
(120181) 2003 UR <sub>292</sub>	Scattered Disk Object	7.093±0.100	1.690±0.080		24
(120216) 2004 EW <sub>95</sub>	Plutino	6.309±0.050	1.080±0.030		24
(121725) 1999 XX <sub>143</sub>	Centaur	8.586±0.096	1.734±0.145		8, 28
(126619) 2002 CX <sub>154</sub>	Scattered or Detached KBO	7.178±0.075	1.470±0.128		31
(127546) 2002 XU <sub>93</sub>	Scattered Disk Object	7.942±0.019	1.200±0.020		21
(129772) 1999 HR <sub>11</sub>	Resonant (7:4)	7.172±0.150	1.450±0.156		16
(130391) 2000 JG <sub>81</sub>	Resonant (2:1)	7.748±0.056	1.417±0.060		This work
(134860) 2000 OJ <sub>67</sub>	Cold Classical	6.001±0.120	1.720±0.078		8
(135182) 2001 QT <sub>322</sub>	Scattered Disk Object	7.752±0.320	1.240±0.060		37
(136108) Haumea	Resonant(12:7)	0.205±0.011	0.973±0.024	Water ice	38, 39, n
(136120) 2003 LG <sub>7</sub>	Resonant (3:1)	8.322±0.049	1.271±0.091		This work

References: see Appendix A

Table A.1 cont'd

Object	Dynamical Class	$H_R(\alpha)$	$B - R$	Spectral features	References
(136199) Eris	Scattered or Detached KBO	$-1.511 \pm 0.033$	$1.207 \pm 0.088$	Methane	24, 36, o
(136204) 2003 WL <sub>7</sub>	Centaur	$8.670 \pm 0.070$	$1.230 \pm 0.040$		24
(136472) Makemake	Hot Classical	$-0.317 \pm 0.024$	$1.332 \pm 0.029$	Methane	36,p
(137294) 1999 RE <sub>215</sub>	Cold Classical	$6.091 \pm 0.073$	$1.700 \pm 0.148$		18
(137295) 1999 RB <sub>216</sub>	Resonant (2:1)	$7.668 \pm 0.096$	$1.419 \pm 0.142$		18
(138537) 2000 OK <sub>67</sub>	Cold Classical	$6.093 \pm 0.083$	$1.540 \pm 0.094$		8
(144897) 2004 UX <sub>10</sub>	Hot Classical	$4.216 \pm 0.087$	$1.530 \pm 0.020$	Methanol	37, i
(145480) 2005 TB <sub>190</sub>	Detached KBO	$3.949 \pm 0.085$	$1.540 \pm 0.030$		21
(148209) 2000 CR <sub>105</sub>	Detached KBO	$6.191 \pm 0.073$	$1.273 \pm 0.068$		21, 25
(148780) Altjira	Hot Classical	$5.885 \pm 0.320$	$1.640 \pm 0.170$		30
(149560) 2003 QZ <sub>91</sub>	Scattered Disk Object	$8.302 \pm 0.028$	$1.305 \pm 0.048$		This work
(168703) 2000 GP <sub>183</sub>	Scattered Disk Object	$5.795 \pm 0.061$	$1.160 \pm 0.057$		8
(181708) 1993 FW	Hot Classical	$6.572 \pm 0.105$	$1.625 \pm 0.110$		1, 17, 19, 22
(181855) 1998 WT <sub>31</sub>	Hot Classical	$7.443 \pm 0.079$	$1.247 \pm 0.140$		28, 40
(181867) 1999 CV <sub>118</sub>	Resonant (7:3)?	$7.067 \pm 0.163$	$2.130 \pm 0.090$		27
(181868) 1999 CG <sub>119</sub>	Scattered Disk Object	$7.004 \pm 0.040$	$1.530 \pm 0.080$		27
(181871) 1999 CO <sub>153</sub>	Cold Classical	$6.607 \pm 0.030$	$1.940 \pm 0.090$		27
(181874) 1999 HW <sub>11</sub>	Scattered or Detached KBO	$6.706 \pm 0.062$	$1.323 \pm 0.043$		21, 27
(182397) 2001 QW <sub>297</sub>	Resonant (9:4)	$6.660 \pm 0.064$	$1.600 \pm 0.070$		21
(182934) 2002 GJ <sub>32</sub>	Hot Classical	$5.469 \pm 0.187$	$1.678 \pm 0.261$		30, 31
1993 RO	Plutino	$8.492 \pm 0.113$	$1.385 \pm 0.154$		1, 9
1994 EV <sub>3</sub>	Cold Classical	$7.110 \pm 0.072$	$1.732 \pm 0.167$		1, 18, 27
1994 TA	Centaur	$11.421 \pm 0.126$	$1.930 \pm 0.155$		9, 7
1995 HM <sub>5</sub>	Plutino	$7.849 \pm 0.109$	$1.010 \pm 0.192$		6, 22
1995 WY <sub>2</sub>	Cold Classical	$6.864 \pm 0.110$	$1.655 \pm 0.278$		1, 7
1996 RQ <sub>20</sub>	Hot Classical	$6.903 \pm 0.092$	$1.523 \pm 0.156$		7, 10
1996 RR <sub>20</sub>	Plutino	$6.622 \pm 0.143$	$1.868 \pm 0.130$		7, 9, 18
1996 TK <sub>66</sub>	Cold Classical	$6.190 \pm 0.116$	$1.666 \pm 0.088$		7, 8, 9
1996 TS <sub>66</sub>	Hot Classical	$5.947 \pm 0.130$	$1.665 \pm 0.157$		6, 7, 12
1997 CV <sub>29</sub>	Hot Classical	$7.154 \pm 0.030$	$1.860 \pm 0.022$		19
1997 QH <sub>4</sub>	Hot Classical	$6.996 \pm 0.136$	$1.731 \pm 0.168$		7, 9, 10, 18
1997 RT <sub>5</sub>	Hot Classical	$7.117 \pm 0.140$	$1.549 \pm 0.162$		18
1997 SZ <sub>10</sub>	Resonant (2:1)	$8.100 \pm 0.104$	$1.790 \pm 0.085$		9
1998 FS <sub>144</sub>	Hot Classical	$6.717 \pm 0.105$	$1.516 \pm 0.057$		19, 22
1998 HL <sub>151</sub>	Hot Classical	$8.120 \pm 0.149$	$1.190 \pm 0.284$		27, 40
1998 KG <sub>62</sub>	Cold Classical	$6.125 \pm 0.110$	$1.602 \pm 0.158$		16, 18
1998 KS <sub>65</sub>	Cold Classical	$7.166 \pm 0.040$	$1.730 \pm 0.045$		19
1998 UR <sub>43</sub>	Plutino	$8.083 \pm 0.132$	$1.390 \pm 0.113$		10
1998 WS <sub>31</sub>	Plutino	$7.952 \pm 0.186$	$1.315 \pm 0.075$		28
1998 WV <sub>24</sub>	Cold Classical	$7.126 \pm 0.067$	$1.270 \pm 0.032$		9
1998 WV <sub>31</sub>	Plutino	$7.627 \pm 0.069$	$1.349 \pm 0.096$		10, 28
1998 WX <sub>24</sub>	Cold Classical	$6.241 \pm 0.099$	$1.790 \pm 0.071$		9
1998 WZ <sub>31</sub>	Plutino	$8.044 \pm 0.102$	$1.263 \pm 0.089$		28
1998 XY <sub>95</sub>	Scattered or Detached KBO	$6.438 \pm 0.143$	$1.580 \pm 0.212$		14
1999 CB <sub>119</sub>	Hot Classical	$6.740 \pm 0.050$	$1.926 \pm 0.095$		28
1999 CD <sub>158</sub>	Resonant (7:4)	$4.837 \pm 0.111$	$1.384 \pm 0.116$		8, 10, 40
1999 CF <sub>119</sub>	Scattered or Detached KBO	$6.982 \pm 0.084$	$1.424 \pm 0.072$		27, 25
1999 CJ <sub>119</sub>	Cold Classical	$6.695 \pm 0.210$	$2.070 \pm 0.220$		27
1999 CM <sub>119</sub>	Cold Classical	$7.356 \pm 0.060$	$1.780 \pm 0.170$		27
1999 CQ <sub>133</sub>	Hot Classical	$6.682 \pm 0.050$	$1.350 \pm 0.070$		27
1999 CX <sub>131</sub>	Resonant (5:3)	$6.914 \pm 0.087$	$1.637 \pm 0.118$		28
1999 GS <sub>46</sub>	Hot Classical	$6.230 \pm 0.020$	$1.760 \pm 0.070$		27
1999 HS <sub>11</sub>	Cold Classical	$6.344 \pm 0.081$	$1.845 \pm 0.099$		16, 19, 28, 35
1999 HV <sub>11</sub>	Cold Classical	$7.003 \pm 0.050$	$1.700 \pm 0.063$		19
1999 JD <sub>132</sub>	Hot Classical	$5.983 \pm 0.020$	$1.590 \pm 0.090$		27
1999 OE <sub>4</sub>	Cold Classical	$6.887 \pm 0.193$	$1.832 \pm 0.147$		28
1999 OJ <sub>4</sub>	Cold Classical	$6.899 \pm 0.060$	$1.675 \pm 0.077$		28
1999 OM <sub>4</sub>	Cold Classical	$7.521 \pm 0.100$	$1.739 \pm 0.170$		18
1999 RJ <sub>215</sub>	Scattered Disk Object	$7.881 \pm 0.103$	$1.221 \pm 0.175$		18
1999 RX <sub>214</sub>	Cold Classical	$6.385 \pm 0.050$	$1.647 \pm 0.070$		28
1999 RY <sub>214</sub>	Hot Classical	$7.006 \pm 0.040$	$1.258 \pm 0.085$		28

References: see Appendix A

Table A.1 cont'd

Object	Dynamical Class	$H_R(\alpha)$	$B - R$	Spectral features	References
1999 TR <sub>11</sub>	Plutino	8.063±0.140	1.770±0.106		9
2000 AF <sub>255</sub>	Scattered Disk Object	5.682±0.030	1.780±0.060		27
2000 CG <sub>105</sub>	Hot Classical	6.469±0.293	1.170±0.170		27, 40
2000 CJ <sub>105</sub>	Hot Classical	5.687±0.066	1.760±0.106		31
2000 CL <sub>104</sub>	Cold Classical	6.394±0.086	1.851±0.192		18
2000 CL <sub>105</sub>	Cold Classical	6.761±0.060	1.520±0.090		27
2000 CN <sub>105</sub>	Cold Classical	5.286±0.160	1.720±0.128		31
2000 CO <sub>105</sub>	Hot Classical	5.619±0.124	1.520±0.180		27
2000 CQ <sub>105</sub>	Scattered Disk Object	5.996±0.054	1.107±0.043		25, 28
2000 FS <sub>53</sub>	Cold Classical	7.165±0.124	1.786±0.095		19, 27
2000 FZ <sub>53</sub>	Centaur	11.103±0.165	1.170±0.050		25
2000 KK <sub>4</sub>	Hot Classical	5.982±0.103	1.550±0.050		19
2000 PE <sub>30</sub>	Scattered Disk Object	5.867±0.110	1.132±0.084		15, 16, 21
2000 YB <sub>2</sub>	Scattered Disk Object	6.436±0.084	1.500±0.134		31
2001 FM <sub>194</sub>	Scattered Disk Object	7.453±0.159	1.190±0.040		25
2001 HY <sub>65</sub>	Hot Classical	6.041±0.064	1.510±0.092		31
2001 HZ <sub>58</sub>	Cold Classical	6.158±0.053	1.640±0.085		31
2001 KA <sub>77</sub>	Hot Classical	5.050±0.089	1.812±0.122		8, 28, 30
2001 KB <sub>77</sub>	Plutino	7.349±0.078	1.390±0.130		24
2001 KD <sub>77</sub>	Plutino	5.928±0.096	1.763±0.060		8, 28
2001 KG <sub>77</sub>	Scattered Disk Object	8.340±0.120	1.240±0.070		25
2001 KY <sub>76</sub>	Plutino	6.689±0.380	1.960±0.291		30
2001 QC <sub>298</sub>	Hot Classical	6.381±0.174	1.030±0.098		31
2001 QD <sub>298</sub>	Hot Classical	6.185±0.170	1.640±0.158		30
2001 QF <sub>298</sub>	Plutino	5.119±0.118	1.051±0.085		15, 24, 30
2001 QR <sub>322</sub>	Neptune Trojan	7.828±0.010	1.260±0.036		41
2001 QX <sub>322</sub>	Scattered Disk Object	6.144±0.146	1.752±0.280		25, 31
2001 QY <sub>297</sub>	Cold Classical	5.151±0.231	1.561±0.177		15, 30, 35
2001 RZ <sub>143</sub>	Cold Classical	6.241±0.123	1.590±0.191		31
2001 XZ <sub>255</sub>	Centaur	10.800±0.080	1.910±0.070		25
2002 DH <sub>5</sub>	Centaur	10.115±0.100	1.054±0.075		28
2002 GB <sub>32</sub>	Scattered Disk Object	7.638±0.019	1.390±0.020		21
2002 GF <sub>32</sub>	Plutino	5.973±0.210	1.765±0.134		30
2002 GH <sub>32</sub>	Hot Classical	6.098±0.201	1.509±0.160		30, 31
2002 GP <sub>32</sub>	Resonant (5:2)	6.580±0.162	1.386±0.162		30, 35
2002 GV <sub>32</sub>	Plutino	6.886±0.199	1.860±0.122		30
2002 MS <sub>4</sub>	Resonant (18:11)	3.333±0.040	1.070±0.040		24
2002 VT <sub>130</sub>	Cold Classical	5.426±0.092	2.010±0.233		31
2002 XV <sub>93</sub>	Plutino	4.434±0.040	1.090±0.030		24
2003 AZ <sub>84</sub>	Plutino	3.537±0.053	1.052±0.057	Methanol	24, 31, 33, h
2003 FZ <sub>129</sub>	Scattered or Detached KBO	6.983±0.038	1.320±0.040		21
2003 HB <sub>57</sub>	Scattered or Detached KBO	7.389±0.028	1.310±0.030		21
2003 QA <sub>92</sub>	Scattered Disk Object	6.367±0.240	1.670±0.020		37
2003 QK <sub>91</sub>	Scattered or Detached KBO	6.966±0.036	1.370±0.040		21
2003 QQ <sub>91</sub>	Scattered Disk Object	7.624±0.280	1.180±0.050		37
2003 QW <sub>90</sub>	Hot Classical	4.730±0.057	1.780±0.092		31
2003 TH <sub>58</sub>	Plutino	6.940±0.056	0.990±0.071		40
2003 UZ <sub>117</sub>	Hot Classical	4.920±0.083	0.990±0.050	Water ice	24, q
2003 YL <sub>179</sub>	Cold Classical	7.482±0.300	1.260±0.090		37
2004 OJ <sub>14</sub>	Scattered or Detached KBO	6.991±0.028	1.420±0.030		21
2004 UP <sub>10</sub>	Neptune Trojan	8.651±0.030	1.160±0.064		41
2004 XR <sub>190</sub>	Detached KBO	3.937±0.036	1.240±0.040		21
2005 CB <sub>79</sub>	Hot Classical	4.375±0.028	1.090±0.028	Water ice	40, q
2005 EO <sub>297</sub>	Resonant (3:1)	7.221±0.047	1.320±0.050		21
2005 GE <sub>187</sub>	Plutino	7.192±0.097	1.740±0.112		40
2005 PU <sub>21</sub>	Scattered Disk Object	6.091±0.019	1.790±0.020		21
2005 SD <sub>278</sub>	Scattered or Detached KBO	5.915±0.019	1.530±0.020		21
2005 TN <sub>53</sub>	Neptune Trojan	9.027±0.040	1.290±0.106		41
2005 TO <sub>74</sub>	Neptune Trojan	8.426±0.030	1.340±0.078		41
2006 RJ <sub>103</sub>	Neptune Trojan	7.400±0.023	1.903±0.044		This work
2006 SQ <sub>372</sub>	Scattered Disk Object	7.709±0.049	1.712±0.093		21, This work

References: see Appendix A

Table A.1 cont'd

Object	Dynamical Class	$H_R(\alpha)$	$B - R$	Spectral features	References
2007 JJ <sub>43</sub>	Hot Classical	4.044±0.019	1.610±0.020		21
2007 JK <sub>43</sub>	Scattered Disk Object	7.028±0.017	1.400±0.027		This work
2007 NC <sub>7</sub>	Scattered Disk Object	8.068±0.018	1.282±0.028		This work
2007 RH <sub>283</sub>	Centaur	8.435±0.039	1.237±0.069		This work
2007 TG <sub>422</sub>	Scattered Disk Object	6.186±0.010	1.390±0.040		21
2007 UM <sub>126</sub>	Centaur	10.161±0.042	1.080±0.096	Water ice	This work, i
2007 VJ <sub>305</sub>	Scattered Disk Object	6.713±0.028	1.440±0.030		21
2008 FC <sub>76</sub>	Centaur	9.181±0.039	1.756±0.024	Methanol	This work, i
2008 KV <sub>42</sub>	Scattered Disk Object	8.564±0.056	1.290±0.060		21
2008 OG <sub>19</sub>	Scattered or Detached KBO	4.612±0.013	1.470±0.010		21

**References:** see Appendix A